

The Biospheric Hazard of Large Impacts

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This brief overview of the impact hazard characterizes the hazard of impacts as a function of meteoroid energy. As reported previously, for impacts below ten megatons energy there is virtually no risk since few meteoroids penetrate the atmosphere. Between ten megatons and the threshold for global catastrophe, impacts are a moderate source of risk, but substantially less so than more common natural disasters such as earthquakes, severe storms, or volcanic eruptions. The greatest hazard is associated with impacts at or a little above a threshold for global catastrophe, where we have defined a global catastrophe to be one that leads to the death of >25% of the Earth's human population. Following the analysis of environmental effects of impacts by Toon et al. (paper given at this conference), we estimate that this threshold lies near one million megatons, corresponding to an average interval between events of about one million years. Above this threshold the entire world population is at risk from impacts, which are the only known natural disasters capable of killing a substantial fraction of the population or, at still larger energies, of threatening the survival of the species. Simple arguments suggest that expenditure of up to several hundred million dollars per year might be appropriate in dealing with such disasters. Arguments for the cost-effectiveness of programs that address the smaller objects (hundred-meter class) impactors are more problematic. Largely independent of proposed mitigation philosophy, however, there is consensus that the first step should be to carry out a comprehensive census of near Earth asteroids such as the proposed Spaceguard Survey to identify any potential impactors.

Introduction

The present conference is a reflection of widespread current interest in the role of impacts in planetary history, and in particular their continuing threat today. The effect of impacts upon the biosphere is most dramatically demonstrated by the discovery (Alvarez et al. 1980) that the K/T mass extinction resulted from the impact of one or more comets or asteroids with a mass (derived from the quantity of extraterrestrial material identified in the K/T boundary layer) of 10^{15} - 10^{16} kg. In this instance a relatively modest cratering event (produced by an object roughly the size of Comet Halley) led to global collapse of ecosystems and the extinction of most terrestrial species, including the dinosaurs.

It is clear that, far short of a mass extinction, a smaller impact could lead to a lesser ecological catastrophe that might nevertheless kill large numbers of people and threaten the stability of society. Such a global catastrophe is qualitatively different from any other natural disaster and can be compared in its consequences only with the result of nuclear war. Interest in all of these impact phenomena was further stimulated by the collision of Comet Shoemaker Levy 9 with Jupiter in July 1994, an event that captured the attention of scientists, the media, and the public at large.

The evaluation of the contemporary impact hazard has developed in tandem with our understanding of the environmental effects of impacts, and particularly their effects on the terrestrial biosphere. The discussion we present here is derived in large part from a series of technical analyses, including the NASA Spaceguard

Survey Report (Morrison 1992). Other relevant publications include discussions by Morrison (1993), Chapman and Morrison (1994), and Morrison, Chapman and Slovic (1994). This paper can be considered a status report updating the conclusions of these previous papers in accord with current research on the biospheric effects of impacts (e.g., Toon *et al.* 1994, 1995).

Nature of the Hazard

The flux of meteoroids striking the Earth is composed of near-Earth asteroids and short-period comets (collectively called Near-Earth Objects or NEOs), and of long-period comets. The asteroids and short-period comets have dynamical similarities; both reside in the inner solar system and generally impact the Earth with speeds of order 20 km/s. Physically, however, they span a wide range of properties, from metal (like the iron meteorites) through various types of rock (like the chondritic and achondritic meteorites) to the low-density, volatile-rich assemblages associated with the comets (Chapman *et al.* 1994). Less is known about the rarer long-period comets, but they are probably also composed of low-density, volatile-rich material. Long-period comets strike with higher velocities, sometimes greater than 50 km/s. Although the physical properties of the impactors can influence their environmental effects, it is clear that for the larger impacts the primary effects are related simply to the kinetic energy of the objects (expressed in megatons (MT), where $1 \text{ MT} = 4.2 \times 10^{15}$ joules). The impact flux was discussed in detail at this conference by Shoemaker.

Based on the average flux of comets and asteroids striking the Earth, we can evaluate the danger posed by impacts of different magnitudes. We have found (Chapman and Morrison 1994; Morrison, Chapman and Slovic 1994) that the concept of energy thresholds is useful for differentiating the qualitatively different effects of impacts, which span a range of 100 million (from 10 MT to 10^9 MT). The concept of a threshold does not necessarily imply a sharp transition from one scale of risk to another, however. The transitions between local blast effects and global catastrophes, for example, may be quite gradual. However, a threshold is useful for discussing the impact energies at which one class of physical effects gives way to another.

The atmosphere protects us from small impacts. An impact with the energy of the Hiroshima nuclear bomb occurs roughly annually, while a one-megaton event is expected at least once per century. Obviously, such relatively common events have not been destroying cities or killing people. Even at megaton energies, most meteoroids break up and are consumed before they reach the lower atmosphere. This is because objects up to tens of meters in diameter are subject to aerodynamic stresses that cause fragmentation and transverse dispersal at high altitude. Only if the object disperses below an altitude of about 20 km is the airburst highly destructive. Numerical models of atmospheric fragmentation and dispersal show that only rocky objects > 50 m diameter (10 MT energy) and cometary objects > 100 m (100 MT energy) penetrate deep enough to pose significant hazards (Chyba *et al.* 1993; Hills and Goda 1993; Chyba 1993).

The area of the surface that is damaged or destroyed by an airburst or a cratering event can be derived in a straightforward way from the known properties of large explosions (e.g., Toon *et al.* 1995). The area of destruction is larger for impacts into oceans than for land impacts as a consequence of the great travel distances of impact-induced tsunamis (Hills *et al.* 1994, Toon *et al.* 1994, 1995). For yields greater than about 10^3 MT, tsunamis associated with oceanic impacts contribute more to the hazard than the direct blast damage of impacts on land or in the continental margins. The detailed nature of the tsunami hazard is a subject for current investigation (see other discussions in these proceedings), but even at our current level of understanding it is clear that objects as small as a few hundred meters in diameter can pose a substantial hazard by this mechanism.

At sufficiently great energies, an impact has global consequences. An obvious if extreme example is the K/T event 65 million years ago. This impact released $> 10^8$ MT of energy and excavated a crater (Chicxulub in Mexico) at least 200 km in diameter. Among the environmental consequences were devastating wildfires and changes in atmospheric and oceanic chemistry as well as a dramatic short-term perturbation in climate produced by some 10^6 of submicrometer dust injected into the stratosphere (Chapman and Morrison 1994, Toon *et al.* 1994, 1995). The K/T impact darkened the entire planet for many months and precipitated a general destruction of terrestrial ecosystems. However, projectiles much smaller than the K/T impactor can still generate a global environmental shock that could severely curtail human agricultural production around the world. Such an agricultural disaster might result in collapse of global economic, social, and political structures. However, we do not know the degree of coupling of these effects, and it is very difficult to estimate the resilience of society to such massive environmental insults. In our previous papers (Chapman and Morrison 1994, Morrison, Chapman and Slovic 1994) we defined a globally catastrophic impact as one that results in the deaths of more

than a quarter of the world's population, due primarily to widespread loss of agricultural production and resulting mass starvation.

In Morrison, Chapman and Slovic (1994), we identified a nominal threshold for a global catastrophe at an impact yield of 3×10^5 megatons, based largely on the work of Toon *et al.* (1994). In this model, the energy threshold for a globally catastrophic impact is determined by the explosive yield required to loft sufficient submicrometer dust into the stratosphere to induce crop failures on at least a hemispheric scale. The more recent analysis (Toon *et al.* 1995 and presentation at this meeting) suggests that a slightly larger impact may be required to produce a climatic effect of this magnitude, with a nominal threshold for global catastrophe of 10^6 MT. The total uncertainty in this threshold value might be as high as an order of magnitude, leading to average frequencies of global catastrophe (as we have defined it) of between 200,000 and 2,000,000 years.

Hazard Analysis

In our previous papers we have addressed the scale of destruction expected for impacts and the numerical hazard associated with impacts of various magnitudes. By numerical hazard we mean the probability of death for an individual due to this event. We will now examine how these estimates might be changed if the threshold size for global catastrophe is at 10^6 MT, and we also consider the effects of the (currently poorly known) tsunamis that can be induced by impacts below this global threshold.

For yields above the threshold energy for global catastrophe (10^6 MT), the number of fatalities is (by definition) > 1.5 billion. If the nominal interval between such impacts is 10^6 yr, the equivalent deaths per year for all impacts above the threshold is about 2000, corresponding to an annual risk of death by impact for an individual of about 1 in 3 million.

The smaller, frequent events larger than the 10-MT atmospheric cut-off (what we may call Tunguska-class impacts) yield equivalent annual fatality rates of only a few tens of deaths/yr for the current world population (Morrison, Chapman and Slovic 1994). The low risk of such impacts is apparent when we realize they take place on land only about once per millennium. This corresponds to a strike in a heavily populated urban region only about once in 10,000 years at current population levels, and considerable longer at historical levels. Thus it is no surprise that we have no record that such impacts have destroyed cities or produced significant casualties over the course of human history. Indeed, aside from two fatalities probably associated with the 1908 Tunguska impact, there are no reliable historical records of any deaths caused by impacts of any size. The average annual risk from such impacts appears to be less than 1 part in 100 million.

Of greater concern is the risk associated with tsunamis, as discussed at this conference by Hills and others. Modeling of impact-induced tsunamis and, even more, of their effects on coasts and coastal populations is an important topic for future work. At present it is possible to conclude with confidence only that the risk is somewhere between that of Tunguska-like land impacts and the global catastrophe associated with yields above one million megatons. Consider, for example, a person living on the Atlantic coast within a few meters of sea level. There are millions of such people on both sides of the Atlantic. Since an impact of a few thousand megatons may be sufficient to generate an Atlantic tsunami, and such an impact might be expected in the North Atlantic about once in 10^5 yrs, these people run an annual risk of a large tsunami of about 1 in 100,000. The equivalent risk of death from the tsunami is obviously much less, depending on warning systems and opportunities for evacuation, but it is possible that for this person the "local" tsunami risk is as much as an order of magnitude greater than the risk from "global" impacts above 10^6 MT. However, only a small fraction of the people on Earth live close to sea level, so the average risk distributed over the entire population falls well below that associated with the global catastrophe (1 part in 3 million).

The most robust conclusion from this hazard analysis is that the average global risk increases monotonically with yield from very low values (annual risk of roughly 1 in 100 million) near the ten-megaton atmospheric penetration threshold up to the million-megaton global catastrophe threshold (annual risk of roughly 1 in 3 million). The shape of this curve is not yet well defined, but total risk summed over all size impactors is probably near 1 in a million. Expressed in terms of equivalent annual monetary value of an effective defense program (Morrison, Chapman and Slovic 1994), the total such value for a United States population near 250 million is of order a few hundred million dollars per year, most of which is associated with the larger projectiles. According to the very rough estimates given here, the tsunami danger itself might justify U.S. defense expenditures of as much as 10^8 dollars/yr.

Comparison with other Hazards

In a rational world, society's response to the threat of impact by an asteroid or comet should be evaluated against other hazards that people face. In a typical year, nearly 1,000 people in the United States alone are killed as a result of being struck by a falling object. None of these objects, at least so far, has been a meteorite, comet, or asteroid.

In the United States, motor vehicle accidents lead the list of hazards, followed by falls, poisoning by solids or liquids, drowning, fires and burns, suffocation, firearms, and poisoning by gas. Still other dangers are widely feared even though fewer than 100 people die per year in the U.S. (e.g., dog bites, lightning, poisonous snakes and spiders). All accidental deaths combined account for approximately 10^5 deaths/yr in the United States (Morrison, Chapman and Slovic 1994).

More useful may be a comparison of the impact hazard with other *natural* hazards. In the United States, the risk of death from natural hazards (earthquakes, hurricanes, tornados, floods, volcanic eruptions) is very low, currently amounting to fewer than 100 deaths/yr, although the occurrence of one major disaster such as a large earthquake in the Los Angeles Basin or a violent eruption of Mt. Ranier near Seattle might dramatically alter these statistics. Even making reasonable allowances for such very rare catastrophes, however, it appears that the average annual risk of death from natural disasters for someone living in the United States or Canada is less than 1 in 10 million (<0.1 parts per million).

The situation is much different in other parts of the world, especially in a few locations that are frequently subject to natural disasters that dwarf anything experienced in North America or Europe. Averaged over the 20th century, the annual risk of death from floods for a person living in Bangladesh has been roughly 1 in 20,000, or 50 parts per million. In China, Japan, and Turkey, the annual risk of death from earthquakes has exceeded 10 parts per million during this century. These values are all more than two orders of magnitude greater than the level of risk from natural hazards experienced in North America and Europe.

Where do impact hazards fit on this scale of natural hazards? In the U.S. and Europe, these risks appear to be of the same (low) order of magnitude as those from the worst other natural disasters, such as earthquakes. However, we have not taken into account the fact that the U.S. and Europe are surely more robust than the global average against impact hazards as well as other natural hazards, so it is likely that here also the impact risk is substantially less than that of other hazards such as earthquakes. This analysis simply has not been done. On a global scale, however, the answer is clear; in many parts of the planet, the impact risk is orders of magnitude lower than that associated with other natural hazards, and only as these other risks are reduced by current and future mitigation programs will the impact hazard seem to be significant.

There is, however, a critical qualitative distinction between impacts and other natural disasters, at least for the case of the global catastrophe associated with impacts above a million megatons. Independent of the maximum energy or destructive power of different modes of natural disasters, they all -- with the possible exception of explosive volcanism -- differ from the globally catastrophic impact hazard in one important respect: they are localized. Even tsunamis, which can extend their reach around the world along ocean coastlines, cannot touch continental interiors. No matter how large the non-impact natural catastrophe, many nations would be unscathed by earthquakes, floods, or storms of the most exaggerated possible scale. Impacts above the million-megaton threshold are unique in producing global consequences at a scale that could threaten the entire world's population simultaneously. That fact alone justifies our continuing concern about these phenomena.

This qualitative distinction also naturally focuses our interest on the larger asteroids and comets, those with impact energies above one million megatons (diameter roughly 2 km for asteroids, 1 km for comets). Any program to mitigate the impact hazard should begin with a comprehensive survey of the larger Earth-crossing asteroids (such as the proposed Spaceguard Survey). Such a survey would provide decades of warning for asteroidal impacts and permit us to develop effective defensive systems, should such an impact threat be identified.

References

- Alvarez, L.W., W. Alvarez, F. Asaro, and H.V. Michel (1980). Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science* 208: 1095-1108.
- Chapman, C., A.W. Harris, and R. Binzel (1994). Physical properties of near-earth asteroids: Implications for the hazard issue. In *Hazards Due to Comets and Asteroids* (T. Gehrels, editor): 537-550. University of Arizona Press, Tucson.
- Chapman, C.R. and D. Morrison (1994). Hazard of impacts on Earth by asteroids and comets. *Nature* 367: 33-40.
- Chyba, C.F. (1993). Explosions of small Spacewatch asteroids in the Earth's atmosphere. *Nature* 363: 701-703.
- Chyba, C. F., P.J. Thomas, and K.J. Zahnle (1993). The 1908 Tunguska explosion: atmospheric disruption of a stony asteroid. *Nature* 361: 40-44.
- Hills, J.G. and M.P. Goda (1993). The fragmentation of small asteroids in the atmosphere. *Astron. J.* 105: 1114-1144.
- Hills, J.G., I.V. Nemchinov, S.P. Popov, and A.V. Teterev (1994). Tsunami generated by small asteroid impacts. In *Hazards Due to Comets and Asteroids* (T. Gehrels, editor): 779-790. University of Arizona Press, Tucson.
- Morrison, D., editor (1992). *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop*. Unpublished NASA report.
- Morrison, D. (1993). The impact hazard. In *Proceedings of the Near-Earth Object Interception Workshop* (G.H. Canavan, J.C. Solem, and J.D.G. Rather, editors): 49-61. Los Alamos National Laboratory.
- Morrison, D., C. Chapman, and P. Slovic (1994). The impact hazard. In *Hazards Due to Comets and Asteroids* (T. Gehrels, editor): 59-92. University of Arizona Press, Tucson.
- Toon, O. B., K. Zahnle, R.P. Turco, and C. Covey (1994). Environmental perturbations caused by impacts. In *Hazards Due to Comets and Asteroids* (T. Gehrels, editor): 791-826. University of Arizona Press, Tucson.
- Toon, O.B., K. Zahnle, D. Morrison, R.P. Turco, and C. Covey (1995). Environmental perturbations caused by the impacts of asteroids and comets. Submitted to *Reviews of Geophysics*.